# REMARKS

## I. Status of the Claims

Claims 1-8 are pending.

Claims 1-8 stand rejected.

Claims 2 and 5 have been amended. No new matter has been added.

## II. Objections to the Specification

The Examiner has objected to the abstract of the disclosure because it did not commence on a separate sheet in accordance with 37 C.F.R. § 1.52(b)(4).

In response, a new abstract of the disclosure is being submitted herewith on a separate sheet.

The Examiner has objected to the specification because the specification as-filed did not include the section headings.in accordance with 37 C.F.R. § 1.77(b).

In response, a substitute specification that includes the section headings is being submitted herewith. Please replace the originally filed specification with the clean copy of the substitute specification submitted herewith. The substitute specification is being submitted to only correct the formal defect identified by the Examiner and no new matter has been added. A marked up version of the substitute specification is also provided in accordance with the requirements of 37 C.F.R. § 1.125.

## III. Claim Objections

The Examiner has objected to claims 2 and 5 because of a number of informalities.

In response, claims 2 and 5 have been amended to correct the informalities as suggested by the Examiner. Accordingly, entry of the amendment of claims 2 and 5 and withdrawal of this objection is respectfully requested.

## IV. Rejection under 35 U.S.C. 102

The Examiner has rejected claims 5-7 under 35 U.S.C § 102(b) as being anticipated by United States Patent No. 5,307,863 to Kubota *et al.* ("Kubota") This rejection is respectfully traversed.

Claim 5 recites "means for regulating at least one of supply voltage and current of each inductor independent of other inductors to maintain the liquid metal flow speeds balanced between the two ports." The recited "means for regulating", as explained in the specification as originally filed, is the feedback arrangement between the current and the voltage control of the individual power supplies for the inductor(s). (The specification as originally filed at page 7, line 18 to page 8, line 8). The "means for regulating" recited in claim 5 includes an individual power supply for each of the inductor(s) where one of the two power supply's output variables, the current and the voltage, is held constant and monitor the other variable. (*Id.*) When there is any disturbance in the speed of the molten metal flow, that variation translates as a variation in the impedance of the inductor(s) responsive to the corresponding induced current. (*Id.*) This causes variation in the other variable of the power supply's output that is being monitored. (*Id.*) This information may then be used as a feedback to control the output of the power supplies for

the other inductor(s) in the installation to control the molten metal flow speed. (*Id.*) Thus, the "means for regulating" recited in claim 5 enables measurement of the molten metal speed during an actual operation of a continuous casting.

In contrast, Kubota does not show or suggest such "means for regulating at least one of the supply voltage and current of each inductor independent of other inductors to maintain the liquid metal flow speeds balanced between the two ports." Neither the portions of Kubota cited by the Examiner nor the remaining disclosure of Kubota disclose or suggest such means. Even if one were to assume, for the sake of argument, that Kubota's Figure 6 shows independent control of the inductors, Kubota's disclosure does not disclose or suggest any monitoring of the output variables of one power supply to be used as a feedback information to control the output of another power supply for other inductor(s).

Furthermore, the disclosure in Kubota explicitly states that the function achieved by the "means for regulating" recited in claim 5 is not possible. Kubota discloses that "the values of the average flow speed of the molten steel and the angle θ <u>cannot be measured</u> in an actual operation of a continuous casting, . . . ." (emphasis added) (Kubota at column 8, lines 55-57). As a remedy to this inability to measure the flow speed of the molten metal during continuous casting, Kubota discloses a method of adjusting the sliding electromagnetic field by modeling the molten metal flow using water in a test structure to determine the excitation frequency of the inductors. (Kubota at column 7, lines 50-55). Thus, Kubota actually teaches away from the invention claimed in claim 5.

The Examiner notes the statement in the originally filed specification in reference to EP 0 550 785 (analogous to Kubota) which states that the present invention "does not modify the structure of conventional installations." The Examiner contends that since there is no

modification to the structure of the apparatus set forth in the prior art, then all apparatus claims would clearly be rejectable under 35 U.S.C. § 102(b). This observation is not applicable to this case, namely, with respect to the apparatus claimed in claim 5 and claims 6 and 7 depending therefrom.

The cited statement from the specification refers to the fact that as in a conventional continuous casting installation with an active sliding field electromagnetic brake, the apparatus of the present invention includes the structures generally found in a conventional installation, such as, a continuous casting mould, an electromagnetic brake comprising at least one inductor and at least one power supply powering the inductor. This does not change the fact that EP 0 550 785 (analogous to Kubota) and Kubota do not disclose the invention recited in claim 5 as discussed above.

Accordingly, withdrawal of this rejection and allowance of independent claim 5 and claims 6 and 7, depending therefrom, are respectfully requested.

## V. Rejection Under 35 U.S.C. 103

The Examiner has rejected claims 1-4 and 8 under 35 U.S.C. § 103(a) as being unpatentable over Kubota in view of WO 99/11403 of Eriksson *et al.* ("Eriksson"). More particularly, the Examiner states that Kubota discloses the apparatus claim limitations set forth in claims 5-7 and it would have been obvious to one of ordinary skill in the art at the time the applicant's invention was made to modify the method and apparatus for continuous casting as disclosed by Kubota by adding the specified control of one or more of the amperage or the voltage of the electromagnets as taught by Eriksson, in order to accurately and independently monitor and control metal flows at portions of the continuous casting mold to avoid

unsymmetrical or unbalanced overall flow, resulting in the reduction of defects in the cast product. This rejection is respectfully traversed.

Independent claim 1 recites a method of measuring the flow speed of a liquid molten metal in an ingot mould equipped with a sliding field electromagnetic brake and the method requires:

(1) supplying the electromagnetic brake with electrical power from at least one constant power source, wherein one of current and voltage of the constant power source's output is held constant;
(2) measuring the other of current and voltage of the constant power source; and
(3) extracting the flow speed of the liquid molten metal from variations in the measurement.

Thus, the method of independent claim 1 requires measuring the flow speed of the molten metal by monitoring the parameters (current or voltage) of the electrical power supplied to the electromagnetic brake in order to determine the flow speed of the molten metal

First, as discussed above in reference to the Examiner's rejection of claims 5-7 under 35 U.S.C. § 102, Kubota does not disclose the apparatus claim limitations set forth in claims 5-7. Kubota actually teaches away from the invention claimed in claims 5-7.

The Examiner's contention that "[o]ne of ordinary skill in the art would have recognized that the parameters and equations set forth by Kubota et al., would enable measurement of dynamic flow speeds at regions within the continuous casting mold, as the apparatus contains molten metal sensors 14, 17, a (servo) control device 16, and magnetic field generators 18 (inductors) that are controlled in terms of voltage, current, and frequency, . . . " is not supported by the disclosure of Kubota. As discussed above in reference to claims 5-7, the disclosure of Kubota explicitly states that "the values of the average flow speed of the molten steel and the angle θ cannot be measured in an actual operation of a continuous casting, . . . ." (emphasis added) (Kubota at column 8, lines 55-57). The molten metal sensors 14, 17 of Kubota are

sensors for detecting positions of the molten metal surface and changes of the positions of the molten metal surface. (Kubota at column 10, lines 16-20). They are not sensors capable of measuring the flow speed of the molten steel in the mould. There is no disclosure in Kubota that shows or suggests that the sensors 14 and 17 or any other devices disclosed therein can be used to measure the flow speed of the molten metal. Thus, Kubota does not disclose, teach, or suggest to one of ordinary skill in the art to supply the electromagnetic brake with electrical power from at least one constant power source, wherein one of current and voltage of the constant power source's output is held constant, and measuring the other of current and voltage of the constant power source to extract the flow speed of the molten liquid metal as required by claim 1.

Moreover, the disclosure of Eriksson does not remedy the above-described deficiencies of Kubota. Unlike the method recited in claim 1, the system of Eriksson does not measure the current or voltage output of the constant power source (of the electromagnetic brake) to extract the flow speed of the liquid molten metal from variations in the measurement. Eriksson discloses a "detection means" for monitoring the flow speed of the molten metal that are devices "such as flow sensors based on eddy-current technology or comprising a permanent magnet, temperature sensors . . ., a level sensing device for determination and supervision of level height and profile of a melt surface in a mold, the meniscus." (Eriksson at page 6, line 23 – page 7, line 5; *see also*, page 13, lines 26-30). The "detection means" are additional sensors. Thus, Eriksson does not disclose using the casting mould's electromagnetic brake and its power source to monitor the flow speed of the molten metal. Thus, Kubota and Eriksson either singly or in combination fail to teach, show, or suggest the method recited in claim 1.

Accordingly, claim 1 and claims 2, 3 and 8 depending therefrom are allowable over Kubota and Eriksson, whether taken singly or in combination. Withdrawal of this rejection and allowance of claims 1, 2, 3 and 8 are respectfully requested.

Independent claim 4 recites:

> a method for regulating the continuous casting speed of a molten metal in an ingot mould equipped with a sliding field electromagnetic brake including several inductors, the method comprising:
>
> supplying to each of the several inductors with electrical power from at least one constant power source individually, wherein one of current and voltage of the constant power source's output is held constant; and
>
> controlling the other of the current and voltage of the constant power source with a measurement of the other of the current and voltage in each inductor.

Thus, the method of independent claim 4 requires holding one of current and voltage of the constant power source (for the inductors) constant, and controlling the other of the current and voltage of the constant power source by measuring the other of the current and voltage in each inductor.

Kubota does not disclose a method in which any of the parameters of the electrical power supplied to the inductors of the casting mould are monitored and used to control the current or voltage of the constant power source for the inductors as required by claim 4.

Moreover, the disclosure of Eriksson does not remedy the above-described deficiency of Kubota. Unlike the method recited in claim 4, the system of Eriksson does not measure the current or voltage output of the constant power source (of the inductors) to control the other of the current and voltage of the constant power source. Eriksson discloses a "detection means" for monitoring the flow speed of the molten metal that are devices "such as flow sensors based on eddy-current technology or comprising a permanent magnet, temperature sensors . . ., a level

sensing device for determination and supervision of level height and profile of a melt surface in a mold, the meniscus." (Eriksson at page 6, line 23 – page 7, line 5; *see also*, page 13, lines 26-30). The information on the flow speed of the molten metal gathered from the "detection means" is used to regulate the magnetic flux density of the magnetic field in the continuous casting mould. (Eriksson at page 6, lines 25-28). Thus, Eriksson does not disclose holding one of current and voltage of each of the inductor's constant power source's output constant, and controlling the other of the current and voltage of the constant power source with a measurement of the other of the current and voltage in each inductor, as required by claim 4. Thus, Kubota and Eriksson either singly or in combination fail to teach, show, or suggest the method recited in claim 4.

Accordingly, claim 4 is allowable over Kubota and Eriksson, whether taken singly or in combination. Withdrawal of this rejection and allowance of claim 4 are respectfully requested.

## VI. Summary

Applicant believes that all of the Examiner's objections and the rejections have been addressed and overcome. Accordingly, reconsideration, withdrawal of the objections and rejections and allowance of the claims are respectfully requested.

If the Examiner believes the prosecution of this application would be advanced by a telephone call, the Examiner is invited to contact the applicant's attorney at the telephone number indicated below.

No fees are believed required for the filing of this Amendment and Response.

Respectfully submitted,

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# METHOD AND INSTALLATION FOR MEASURING AND REGULATING THE FLOW RATE OF A LIQUID METAL IN A CONTINUOUS CASTING INGOT MOULD



## BACKGROUND OF THE INVENTION

### FIELD OF THE INVENTION

[0001] The present invention relates to metallurgic installations and, more specifically, to installations of continuous casting of a liquid metal in an ingot mould.

### DESCRIPTION OF RELATED ART

[0002] Fig. 1 very schematically and partially shows in a perspective view, the inlet section of a continuous metallurgic casting ingot mould 1. The ingot mould essentially includes a mould 2, open at its two ends in the case of a continuous casting. The liquid metal is brought into the ingot mould by an immersed nozzle 3, plunged into the mould 2. Nozzle 3 has lateral ports 4 which aim at giving a horizontal component to the speed of the liquid metal at the outlet of nozzle 3.

[0003] Fig. 2 is a simplified cross-section view of a conventional ingot mould 1 illustrating, with arrows, the motions of the liquid metal in the inlet section of mould 2. As illustrated in Fig. 2, the horizontal component of the liquid metal speed, given by ports 4 of nozzle 3, limits the vertical penetration depth of the metal supply stream into mould 2. Liquid metal l comes, for example, from a crucible 5 (for example, of blast furnace type). In the example shown in Fig. 2, crucible 5 includes, in its lower portion, an opening 6 associated with a controllable closing means 7 for controlling the liquid metal poured into nozzle 3. In conventional installations, the speed of the liquid metal at the outlet of nozzle 3 can reach several meters per second. It is thus important to be able to control the liquid metal penetration in the cast. Indeed, too large a penetration of this liquid metal raises several problems. Among these, the dragging of non-metallic particles coming from the powder or skin (not shown) which covers ingot 8 cast in mould 2 should be noted. These particles are trapped in the obtained metal. Too large a penetration of the liquid metal also causes an inverted thermal gradient since the hot liquid metal has an effect upon the deep regions of the cast and causes, in particular, a local remelting deep into the at least partially solidified ingot, which also adversely affects the quality of the product.

**[0004]** To limit the liquid metal speed, braking systems and, in particular, electromagnetic brake systems, are used.

**[0005]** A first type of electromagnetic brake uses a D.C. magnetic field in a direction perpendicular to the metal flow, which generates induced currents. The induced currents interact with the applied magnetic field and generate an electromagnetic force which is a braking force aiming at nullifying the speed having caused the induced currents. Such D.C. magnetic field systems are generally formed of an electro-magnet totally or partially surrounding the ingot mould, and which generates a magnetic field transversal to the liquid metal. Such systems have the disadvantage of being passive, that is, the magnetic field has a geometry and a position which are set once and for all, whereby any divergence at a given operating point reduces the braking efficiency. Accordingly, this braking appears to be inefficient when the supply conditions (speed, nozzle shape, nozzle port immersion depth, etc.) change.

**[0006]** A second category of so-called sliding field electromagnetic brakes uses an A.C. magnetic field generated by a polyphase power supply applied to inductors exhibiting an adapted space distribution. The magnetic field is thus given a rotation or translation motion according to whether the inductor shape is cylindrical or planar. Such magnetic fields enable accelerating or slowing down the liquid metal flow in continuous metallurgic castings. Thus, the system is active since the mechanical effect induced in the liquid metal is independent from the liquid speed and is controlled by the operator.

**[0007]** The present invention more specifically relates to continuous casting installations equipped with a sliding magnetic field electromagnetic brake system.

**[0008]** In practice, in industrial continuous metallurgic casting installations, a sliding magnetic field brake is formed of four sliding field inductors associated by pairs on each side of mould 2 of the ingot mould. In Fig. 1, two of these inductors have been schematically illustrated and designated with reference 9. In Fig. 2, the two inductors have been illustrated in dotted lines. On a same side of the ingot mould, the two inductors are, as illustrated in Fig. 1, symmetrically arranged with respect to the axis of nozzle 3 on either side thereof to balance the metal distribution.

[0009] An example of an electromagnetic brake in a metallurgic casting installation is described, for example, in European patent application N°0,550,785, the content of which is incorporated herein by reference.

[0010] A problem posed is that the geometry of ports 4 of nozzle 3 varies along time, in particular, due to an erosion of these ports due to the fast flow of the liquid steel in the nozzle. This erosion does not necessarily evolve symmetrically, which then results in a hydrodynamic dissymmetry in the ingot mould due to a stronger flow on one side of nozzle 3 than on the other. Such an imbalance adversely affects the quality of the finished product, since it results, not only in the introduction of non-metallic particles coming from the liquid metal skin, but also in different solidification durations from one side of the formed ingot to the other.

[0011] It is thus desirable to be able to differentiate the actions of sliding magnetic field inductors 9 to restore a balanced injection in the ingot mould.

[0012] For this purpose, it could be thought to separately supply the four inductors to provide many combinations in the organization of the liquid metal motions. In particular, the braking of the liquid metal flow on one side or the other of nozzle 3 could then be individualized.

[0013] However, the theoretical individualizing of the effects of the different inductors on the metal cast poses implementation problems due, in particular, to the need to then know the actual speed of the metal cast at a given time. Further, the current metal injection speed must be known on either side of nozzle 3.

[0014] A conventional method to adjust the sliding electromagnetic field in an ingot mould of the type illustrated in Figs. 1 and 2 consists of modeling the flow in a test structure using, for example, water to determine the excitation frequency of the inductors. Such a method is described, in particular, in above-mentioned European patent application N°0,550,785.

[0015] Clearly, such a method cannot enable knowing in real time the speed of the flow through both ports 4 of nozzle 3 and, more specifically, detecting an imbalance in this flow.

[0016] A first solution to know this speed would be to use stress gauges attached to rods dipped into the liquid steel of the ingot mould. By measuring a signal linked to

the hydrodynamic effort exerted by the liquid steel on the rods, any flow dissymmetry can be detected and, accordingly, corrected by modifying the power injected in inductors 9. However, the use of rods, for example, alumina rods, poses several problems.

**[0017]** A first problem is that such rods form an intrusive element in the ingot mould which is likely to introduce pollution in the obtained product, in particular, by an erosion of the rods due to the liquid metal cast.

**[0018]** Another disadvantage is that the wearing by erosion of these measurement rods makes this solution, in practice, hardly viable from an economical point of view, due to the high consumption of alumina rods in an industrial process.

## SUMMARY OF THE INVENTION

**[0019]** The present invention aims at overcoming the disadvantages of conventional continuous metallurgic casting installations. The present invention more specifically aims at enabling individualized control of the inductors of a sliding field electromagnetic brake of such an installation.

**[0020]** The present invention also aims at providing a solution which causes no pollution of the liquid metal during casting.

**[0021]** The present invention also aims at providing a solution which is particularly economical and requires no consumable material replacement.

**[0022]** The present invention further aims at providing a solution which is particularly adapted to an individualized control of the powers injected into the inductors generating the sliding magnetic field.

**[0023]** To achieve these objects, the present invention provides a method for measuring the flow speed of a liquid molten metal in an ingot mould equipped with a sliding field electromagnetic brake, consisting of measuring the voltage or the current of at least one power source of the electromagnetic brake and extracting the flow speed from this measurement.

**[0024]** According to an embodiment of the present invention, the method is applied to an electromagnetic brake, at least one inductor of which includes two batches of several conductors in a vertical direction, and consists of applying, for each conductor, the following relation:

$\mathrm{grad}V = -i(\omega - vk)A - \rho j$,

[0025] where ω represents the A.C. excitation pulse of the sliding field, v represents the metal speed, k represents the wave number of the inductive sliding magnetic field, A represents the vector potential, ρ represents the resistivity of the metal, j represents the density of the excitation current of the conductor, and V represents the voltage across the inductor.

[0026] According to an embodiment of the present invention, the speed measurement is used to servocontrol the excitation of the inductors onto a predetermined value.

[0027] The present invention also provides a method for regulating the continuous casting speed of a molten metal in an ingot mould, consisting of controlling the voltage or the current of at least one supply source of a sliding field electromagnetic brake including several inductors, with a measurement of the current or of the voltage in each inductor.

[0028] The present invention also provides a continuous casting installation of the type using a sliding field electromagnetic brake to control the flow of a liquid metal provided by two ports of a nozzle, characterized in that each inductor of the electromagnetic brake is powered by an individual circuit; and in that the installation includes means for regulating the supply voltage or current of each inductor to maintain the liquid metal flow speeds balanced between the two ports.

[0029] According to an embodiment of the present invention, each supply circuit of each inductor includes its own means for regulating the electromagnetic excitation power of this inductor.

[0030] According to an embodiment of the present invention, the installation includes a central station for controlling the supply circuits of the different inductors to regulate the liquid metal flow speed.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0031] The foregoing objects, features and advantages of the present invention will be discussed in detail in the following non-limiting description of specific embodiments in connection with the accompanying drawings, among which:

[0032] Figs. 1 and 2, previously described, show an example of a continuous metallurgic cast installation of the type to which the present invention applies;

[0033] Fig. 3 very schematically shows the respective positions of the inductors in a continuous casting system to which the present invention applies;

[0034] Fig. 4 is a top view of an ingot mould equipped with a casting speed control system according to the present invention; and

[0035] Fig. 5 schematically shows an embodiment of a circuit for controlling an inductor according to the present invention.

DETAILED DESCRIPTION

[0036] The same elements have been designated with the same references in the different drawings. For clarity, only those elements which are necessary to the understanding of the present invention have been shown in the drawings and will be described hereafter. Reference can be made to literature, in particular, to European patent application N°0,550,785, for the forming of a continuous casting installation with an active sliding field electromagnetic brake, since the present invention does not modify the structure of conventional installations.

[0037] A feature of the present invention is to take advantage of an individual power supply of the different inductors of a sliding field electromagnetic brake to extract, from the electric characteristics of this inductor supply, information concerning the flow speed of the liquid metal in the ingot mould.

[0038] According to the present invention, the fact that the currents induced by the conductive liquid metal in the magnetic field created by the inductors depend, among others, on the liquid metal flow speed, is used. In particular, assuming that the system is stabilized for a metal speed corresponding to a permanent liquid metal flow state, any disturbance which causes a variation in this speed translates as a variation in the impedance of the inductor(s) responsive to the corresponding induced current. Thus, according to the present invention, a constant power source, either in current, or in voltage, is used to supply the inductors, and the possible variation of the other variable (voltage or current) is examined to deduce a variation in the liquid metal flow speed. Further, due to the fact that the inductors are powered separately from one another this

speed can be localized. This information may, in a preferred embodiment, be used as the feedback of a system of control of the power supply of the different inductors to control the metal flow speed with a point of equilibrium corresponding to a given speed reference, for example, calculated based on a modeling such as described in European patent application N°0,550,785.

**[0039]** Fig. 3 very schematically illustrates the position of four inductors in a continuous casting installation. For simplification, only inductors 9 and a parallelogram symbolizing liquid metal 1 between these inductors have been shown.

**[0040]** Conventionally, each inductor 9 is formed of several imbricate turns adapted to being respectively supplied by different phases. In the example of Fig. 3, a two-phase electromagnetic brake system has been assumed. Each inductor 9 thus includes two circuits, respectively 10 and 11, of conductive imbricate turns in a magnetic yoke 12 opposite to metal 1 with respect to plane x-z in which are inscribed conductive circuits 10 and 11. A first conductive circuit 11 corresponding to a first phase is formed of three packs of conductors 13, 14, 15. The number of conductors of the central pack 15 corresponds to twice the number of conductors of packs 13 and 14 which surround two packs 16, 17 of conductors of second circuit 10 intended to be supplied by the second phase of the two-phase power supply. To form the adapted ampere-turns, the conductor batches are directly connected by phase to one of their ends and, via the supply source (not shown in Fig. 3), to their other respective ends. Thus, in the example of Fig. 3 where the vertical axis z is in the cast direction and the horizontal axes x, y, are respectively in the largest direction of liquid metal 1 corresponding to the alignment of the ports (4, Fig. 1) of the injection nozzle and in the smallest direction of liquid metal 1, the conductor packs of the different inductors are in the vertical direction z. They are, for example, directly connected by their respective lower ends. By the connection of the conductor packs, the turns are run through by a current which, in the vertical sections, is inverted according to whether conductors 13, 14, or 15 for first circuit 11, and 16 or 17 for second circuit 10 are involved. To illustrate this flow in opposite directions, an example of current flow, symbolized by a "." or a "x" according to the flow direction in the vertical sections, has been indicated in Fig. 3.

[0041] The current flow as shown in Fig. 3 is conventional and will not be detailed any further. It should only be noted that the present invention may be implemented in a system including a greater number of phases, for example, in a three-phase or polyphase system while respecting the usual phase imbrication to obtain a polyphase sliding field. It should also be noted that, as illustrated by the representations of the current flow directions in Fig. 3, axis x corresponds to a longitudinal axis of symmetry which in fact is an axis of antisymmetry for inductors 9 which are opposite two by two.

[0042] In a sliding field electromagnetic field such as illustrated by the preceding drawings, it can be considered that the potential vector A, the current density j, and the electric field E have a single component along vertical axis z, that the speed of induced metal v has a single component along longitudinal axis x, and that the magnetic induction B has two components along horizontal axes x and y.

[0043] The synchronism speed vs of the sliding electromagnetic field is equal to the product of the operating frequency f of the A.C. excitation of the two phases by the wavelength $\lambda$ of the sliding field wave. It should be noted that the actual speed v of the metal is opposite to this synchronism speed which also has one component only along longitudinal axis x.

[0044] The equations which govern the operation of the electromagnetic field, respectively in the inductor, in the air, in the magnetic yoke, and in the induced metal, may be expressed as follows in projection on vertical axis z where the single unknown value is component A along Oz of potential vector $\vec{A}$.

[0045] In the inductor, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}(\xrightarrow[\text{grad}]{} A\right] = J_i,$$

where Ji represents the current density imposed in the inductor by the power supply, and where $\mu_0$ represents the permeability of vacuum.

[0046] In the air, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}\left(\overrightarrow{\text{grad}}A\right)\right] = 0.$$

[0047] In the magnetic yoke, one may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0\mu_r}\left(\overrightarrow{\operatorname{grad}A}\right)\right]=0,$$

where $\mu_r$ is the relative permeability of the magnetic medium.

[0048] In the induced metal, on may write:

$$-\operatorname{div}\left[\frac{1}{\mu_0}\left(\overrightarrow{\operatorname{grad}A}\right)\right]=i\frac{\omega}{\rho}A\frac{v}{\rho}\frac{\partial A}{\partial x},$$

where $\omega$ represents the electric pulse of the A.C. power supply ($\omega = 2\pi f$) and where $\rho$ represents the resistivity of the liquid metal.

[0049] As a first approximation, to neglect edge effects, it can be considered that the potential vector A is a sliding wave due to an infinitely long inductive sheet following longitudinal direction x. It can then be considered that the only component A of the vector potential according to vertical axis z can be written as:

$$A = A_0 e^{i(\omega t - kx)},$$

where k represents the wave number of the inductive sliding magnetic field ($k = 2\pi/\lambda$).

[0050] With this approximation, the preceding relation in the induced metal can be expressed in projection on the vertical axis as being equal to:

$$-\operatorname{div}\left[\frac{1}{\mu_0}(\overrightarrow{\operatorname{grad}A})\right]+\frac{i}{\rho}(\omega - vk)A=0.$$

[0051] Introducing the synchronism speed of the inductor in this equation provides:

$$-\operatorname{div}\left[\frac{1}{\mu_0}(\overrightarrow{\operatorname{grad}A})\right]+i\frac{2\pi}{\lambda\rho}(v_s - v)A=0.$$

[0052] All the above expressions show that the only variable quantities for a given current are potential A and speed v of the liquid metal.

[0053] It should be noted that, rather than the current, the current density must be set. However, the number of conductors per pack (that is, the number of turns) has no incidence since the voltage variation of each phase will be compared in a relative manner for a metal speed variation.

**[0054]** Voltage gradient gradV can thus be calculated based on the respective values of potential vector A, of imposed current density j, and of the previously established relations.

**[0055]** By projecting on vertical axis z the following Maxwell equation:

$$\vec{j} = \sigma\left(-i\omega\vec{A} + \vec{v}\times\vec{B} - \overrightarrow{\mathrm{grad}}V\right) = \sigma\left(-i\omega\vec{A} + \vec{v}\times\overrightarrow{\mathrm{rot}} \xrightarrow[A]{} \overrightarrow{\mathrm{grad}}V\right)$$

which links values j, gradV and A, and by replacing $\vec{v}\times\overrightarrow{\mathrm{rot}\vec{A}}$ by ivkA, the following relation giving the voltage gradient on each conductor is obtained:

gradV = -i(ω-vk)A - ρj.

**[0056]** It is then sufficient to sum up the values obtained for all the conductors in each pack to obtain the total voltage of the respective phases. If need be, the impedance of each phase, rather than the voltage, may be deduced by dividing this voltage by the currents imposed by current sources 31 and 32.

**[0057]** As a specific example of implementation, taking for each conductor pack a rectangle of 160x100 $mm^2$ (except for end packs 13 and 14 which each correspond to a rectangle of 80x100 $mm^2$), the current density is $6.75\times10^6$ amperes rms per $m^2$. Assuming a relative permeability $\mu_r$ of 1,000, the wavelength λ of the sliding field is approximately 1.3 m. For an operating frequency of, for example, 0.65 Hz, the synchronism speed $v_s$ is 84.5 cm/s.

**[0058]** Assuming, in a simplified manner, that the induced metal is a solid of constant resistivity $\rho = 100.10^{-8}$ Ωm (which corresponds to a conductivity of $1.10^6$ $(\Omega m)^{-1}$, that is, substantially that of liquid steel), the respective values of the total voltage for the conductor packs may be calculated for two modules of liquid metal speed of 10 and 9 cm/s. For example, for batches 16 and 17 of 40 conductors having a square cross-section of 20x20 $mm^2$ in series, which amounts to considering batches of 40 spirals in each of which flows a current of 2700 A rms, voltages of 38.66 volts and 36.74 volts in modulus are obtained for, respectively, 10 cm/s and 9 cm/s. Accordingly, the modulus of the voltage of the corresponding phase decreases by approximately 2/38, that is, approximately 5%. On the impedance of the corresponding phase, the variation also is on the order of 5% for a same metal speed variation.

[0059] Accordingly, it can be considered that with industrial values, a variation on the order of 10% of the metal speed causes a variation on the order of from 5 to 6% in the voltage and in the impedance. This variation is substantial enough to be used to control the regulation circuits to bring the speed back to its mean reference value, or to bring down to zero an interval between two values.

[0060] Fig. 4 illustrates, in a top view of an ingot mould, the respective electric connections according to the present invention of the two-phase inductors illustrated in Fig. 3. The direct connections between the difference conductor packs, for example, in the lower portion of the system, have been symbolized by dotted lines.

[0061] In the top view of Fig. 4, nozzle 3 has been schematically at the center of mould 2. Each inductor 9 has been symbolized by its magnetic yoke 12 and its two conductive circuits 10, 11 formed, in the vertical direction, respectively of two packs 16, 17 of a same number of conductors and of three packs 13, 14, 15, the central pack 15 having a number of conductors which is twice that of end packs 13 and 14.

[0062] As indicated previously, sections 16 and 17 of each circuit 10 are directly connected, for example, by a cable 18 in their lower portion. Similarly, packs 13 and 14 are each connected to pack 15, for example, by cables, respectively 19 and 20. In the upper portion of the vertical conductive packs, said packs are connected by their ends to supply means. According to the present invention, conductive circuits 10 and 11 of each inductor 9 are individually connected to a supply circuit 21 specific to the concerned inductor. Thus, packs 13 and 14, pack 15, pack 16, and pack 17 are connected to a circuit 21 by respective cables 22, 23, 24, and 25.

[0063] According to the present invention, all circuits 21 have an identical structure which will be described hereafter in relation with Fig. 5. Each circuit is individually connected to a central control station 26, for example, by cables 27. Cables 27 have been illustrated as including several independent conductors to bring, to each supply circuit 21, the different necessary A.C. supply phases as well as, if necessary, appropriate control signals provided by central station 26. It should however be noted that only the control signals could be individualized and that the polyphase supply conductors could be common to the different circuits 21, said circuits then being in charge of adapting the respective powers to be provided to each of the inductors.

[0064] For clarity, the different references of inductors 9 have been indicated only once in Fig. 4, each inductor having a similar structure and differing from the others by the current flow direction only, as illustrated in Fig. 3.

[0065] Fig. 5 very schematically shows the structure of a supply circuit 21 of an inductor according to the present invention.

[0066] In the example of Fig. 5, it is assumed that each inductor phase is supplied by a low-frequency A.C. signal, of which the rms current value is set to a predetermined value according to the nominal braking characteristics desired for the ingot mould. Thus, circuit 21 of Fig. 5 includes two current sources 31 and 32 supplying, for example, cables 23 and 25 respectively associated with conductor packs 15 and 16 as illustrated in relation with Fig. 4. Current sources 31 and 32 are, according to the present invention, controllable, respectively, by signals 33 and 34 provided by regulation circuits, respectively 35 and 36. Each circuit 35, 36, measures the voltage between, respectively, conductors 22 and 23 and conductors 24 and 25. These voltage measurements are intended to evaluate the liquid metal speed opposite to the corresponding inductor.

[0067] In the embodiment illustrated in Fig. 5, each regulator 35, 36 receives a reference 37, 38 from the control station 26 (Fig. 4) and is in charge of controlling the current provided by sources 31 and 32 to enable a regular and balanced speed in the ingot mould. However, the regulation may also be provided to be performed directly by central station 26, or a voltage regulation may be provided to be used to calculate the speed, so that it is exploited by the central station 26.

[0068] Of course, the inductors may also be supplied by a controllable voltage of predetermined value, and a current measurement, the variations of which will then depend on the speed, may be used, thus enabling feedback on the supply voltage source.

[0069] The practical implementation of the method according to the invention, by the forming of electronic circuits or the programming of computing tools necessary for the calculation, is within the abilities of those skilled in the art based on the functional indications given hereabove. It should be noted that the complexity of this electronic circuit or of the programming computations will depend on the desired accuracy for the control, as for any conventional control.

[0070] An advantage of the present invention is that it enables measuring the liquid metal speed in the ingot mould without any physical contact with the liquid metal.

[0071] Another advantage of the present invention is that it is particularly well adapted to a control of continuous casting systems since it is very easy to have a feedback on the current or the voltage in the inductors.

[0072] Another advantage of the present invention is that it requires no modification of conventional continuous casting installations with a sliding field electromagnetic brake, except for the control circuits of the different inductors.

[0073] Of course, the present invention is likely to have various alterations, improvements and modifications which will readily occur to those skilled in the art. In particular, the adaptation of the method according to the number of phases of sliding field electromagnetic brake systems is within the abilities of those skilled in the art according to the application and to the functional indications given hereabove. Further, the numerical values indicated in the foregoing description have been indicated only to show the industrial feasibility of the present invention and for illustration only. Further, it should be noted that the present invention may be implemented in any continuous casting system, whatever the shape of the ingot mould, provided that it uses an active sliding field electromagnetic brake system.

ABSTRACT OF THE DISCLOSURE

A method for measuring flow speed of a liquid molten metal in an ingot mould equipped with a sliding field electromagnetic brake, consisting of measuring the voltage or the current of at least one power source for the electromagnetic brake and extracting the flow speed from this measurement.